Carbon use for synthetic materials in Germany — current situation and saving potentials for energy and CO_2

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Abstract

This study deals with the use of fossil carbon (oil, natural gas, coal) to manufacture materials ('products of non-energy use') and with the potential to reduce the inputs of fossil resources and the emissions of fossil CO_2 in Germany. An overview of the material flows is given for Germany in 1995. Recycled and re-used products still accounted for less than 10% of the end products consumed domestically. The energy requirements and CO_2 emissions from the production and waste management processes related to non-energy use have been calculated: it is estimated that approximately 1700 PJ of finite primary energy are consumed and 57 Mt of fossil CO_2 emissions are released (1995). Compared with the total German industry (without non-energy use) this represents 44% of the energy use and 20% of the fossil CO_2 emissions. Detailed analyses are performed in order to determine the extent to which the energy consumed by and the CO_2 emissions released from this system could be reduced. This is done by estimating the possible effects of (a) using waste as a resource, and (b) using biomass as a feedstock. In the first group recycling, re-use and enhanced energy recovery are investigated for plastics, discarded tyres, technical rubber products, asphalt, industrial bitumen and waste lubricants. The second group, i.e. the analysed bio-based materials, comprises of oleochemical surfactants, lubricants from vegetable oils, starch polymers and

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selected bulk chemicals. The total potential savings related to waste use and biomass use (see above (a) and (b)) are estimated at 220 PJ of gross finite energy and 14 Mt of gross fossil CO_2. This is the equivalent of a 13% saving in energy and a 24% reduction in CO_2 emissions. Hence, the saving potential identified on the non-energy side is comparable with the saving potential discussed and negotiated for CO_2 mitigation through energy efficiency improvements. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Much of the discussion related to climate change has focussed on the emissions of greenhouse gases (GHGs), the most important one being carbon dioxide (CO_2) [1]. Being the main source of CO_2, the combustion of fossil fuels has so far been at the centre of attention. However, a significant fraction of fossil fuels is also used for 'non-energy' applications and this may also be relevant to climate change [2]. 'Non-energy use' is defined as the consumption of carbon feedstocks for the manufacture of synthetic materials and chemical products, e.g. plastics, fibres, synthetic rubber, paints, solvents, fertilizers, lubricants and surfactants. In principle, most of these products can be manufactured from carbon sources of both fossil and biomass origin. However, since the contribution from biomass sources for non-energy use is relatively small, it is usually disregarded in energy balances. Therefore, non-energy use is usually defined as the consumption of *fossil* carbon feedstocks.

Non-energy use represents 11–12% of the total amount of fossil fuels for final consumption in the 15 countries of the European Union (EU-15, values for 1995/1996) [3]. Within the EU-15, the share of non-energy use differs from country to country. For example, while the share in the Netherlands is in the range 16–20%, it is about 10–11% in Germany (1995/1996) [3]. German non-energy use in 1995, i.e. the amount of fossil carbon used as chemical feedstock, was equivalent to approximately 77 Mt[2] of CO_2 [4]. However, only a part of this is released in the short term through industrial processes (steamcracking, methanol and ammonia production), the treatment of solid and liquid production waste, wastewater treatment and short-lived products, e.g. solvents. The remainder might be emitted in the long term [2]. While plastic products, for example, will virtually not result in CO_2 emissions in the short term if they are landfilled, they are fully oxidised to CO_2 if incinerated. On the other hand, plastics incinerated in municipal solid waste incineration (MSWI) plants may, to some extent, substitute the use of fossil fuels if the plant produces electricity and/or steam (waste-to-energy facilities). Moreover, technology for recycling and re-use might help to reduce the energy requirements of the entire system and curb CO_2 emissions [5]. This might also be true for the increased use of biomass to produce chemicals, which can replace conventional products made of fossil feedstocks [6]. To ensure a fair comparison to the various

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[2] Mt stands for 10^6 metric ton (megaton).

options, all energy and material inputs along the entire process chain need to be accounted for (see Section 2.2).

This study is a synthesis of earlier work revolving around non-energy use in Germany. The details of the analyses underlying this study can be found in [4,11,29,31,32,38,52,58]. This study presents

1. an inventory of the flows of all materials made from fossil carbon ('products of non-energy use'), including the manufacture and foreign trade at the various levels of production as well as the generation of waste and waste management in the year 1995;
2. the energy requirements of — and the fossil CO_2 emissions from — this system;
3. the evaluation of a selection of measures that are possible for improving the resource efficiency and reducing CO_2 emissions within this system; and
4. estimates of the short-term technical saving potential for energy and CO_2 for the system analysed.

This study presents the major results of the analyses. The study did not include an assessment of the *energy efficiency* potentials in production processes (e.g. [7–9]) nor of the possibility to use renewable energies to fuel the processes[3] (*bioenergy*, e.g. [10]).

An overview of the methodology that has been used is given first of all. This is followed by a description of the current situation, including an inventory of the material flows, the energy requirements, and CO_2 emissions of the system. The third chapter discusses the measures and potentials to improve resource efficiency and reduce carbon emissions. The study closes with a discussion of the results and some conclusions.

2. Methodology

Fig. 1 shows the scheme of the material flow model. The products and processes included in the various modules are listed in Table 1. The material flows, energy requirements and CO_2 emissions of synthetic organic products in the production chain and in the waste management section are simulated by a total of 13 coupled modules. Four production levels are distinguished in the production process chain. They are represented by the modules for the production of fuels (module AB), basic chemicals (module BC), intermediate products/materials (module CD), and end products (module DE). In the following service module (module EF), the use phase of the end products is modelled, products consumed at a certain point of time are

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[3] This statement refers to the generation of steam, electricity, and other forms of energy produced from biomass in dedicated processes, e.g. the gasification of wood and natural organic household waste for electricity production. This type of processes is usually referred to as 'bioenergy' and it is not included in this study. However, this study does cover the energy recovery from products, which contain biogenic carbon, e.g. from tyres, which contain natural rubber. It should be noted here that the amount of biogenic carbon in all synthetic organic materials is very small. Therefore, energy recovery from synthetic organic materials containing biogenic carbon plays a minor role in this analysis.
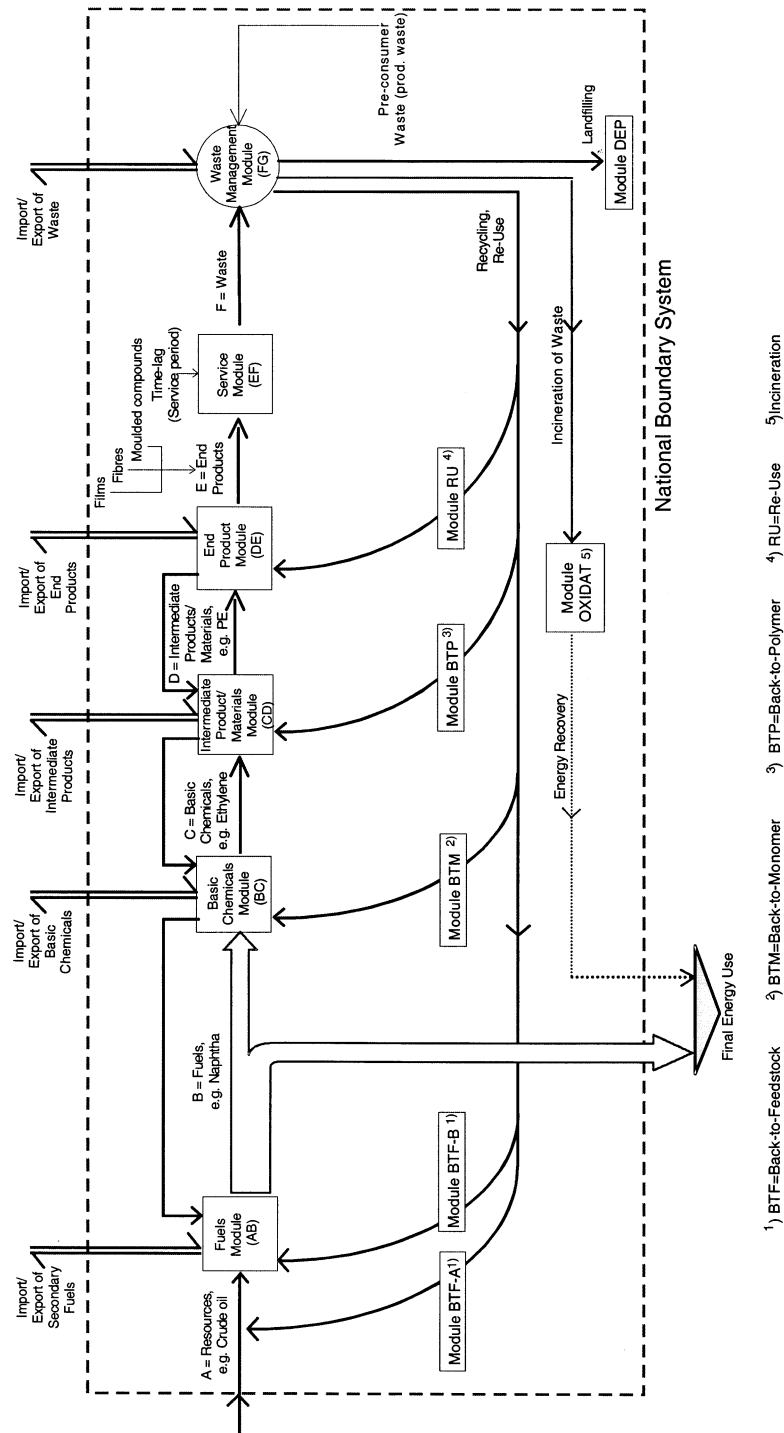
Fig. 1. Material flow models for the manufacture, use, and waste management of synthetic carbon products.

Table 1
Products and processes included in the model

Secondary fuels module (AB)		Basic chemicals module (BC)		Intermediate product/materials module (CD)		End product module (DE)		Recycling and energy recovery (BTF, BTM, BTP, RU, OXIDAT)	
1	Hard coal (coking plants exclude)	1	Methanol from brown coal	1	PVC	1	Synthetic fibres		*Plastics*
2	Coking plants, hard coal	2	Production of calcium carbide (without hydrolysis)	2	LDPE and LLDPE	2	Plastics films/sheets	1	Mechanical recycling of mixed plastics waste
3	Soft coal (coking plants exclude)	3	Acetylene from calcium carbide	3	HDPE	3	Plastics packaging materials	2	Mechanical recycling of PVC
4	Coking plants, brown coal	4	Processing of raw tar	4	PP	4	Moulded plastics compounds	3	Mechanical recycling of PET
5	Refineries	4a	Processing of raw tars and ammonia production in coking plants	5	Other polyolefins, EPDM	5	Foamed plastics	4	Mechanical recycling of EPS
6	Natural gas	4b	Production of carbon black	6	Polyvinylacetate (PVAc) etc.	6	Non-plastics	5	Alcoholysis of PET

Table 1 (*Continued*)

Secondary fuels module (AB)	Basic chemicals module (BC)		Intermediate product/materials module (CD)		End product module (DE)		Recycling and energy recovery (BTF, BTM, BTP, RU, OXIDAT)	
	5	Processing of raw benzene for chemical use and production of chemicals in refineries	7	Polystyrene (PS) and copolymers	7	Other plastics items	6	Decomposition of polyamides
	6	Steamcracking of naphtha	8	Polyacrylates	8	Rubber products	7	Recycling of PUR
	7	Steamcracking of gas oil	8a	Polyacrylonitrile	9	EG as antifreeze agent	8	PARAK process[a]
	8	Methanol from fuel oil	8b	Other polyacrylates	10	Surfactants from EO	9	Gasification (SVZ process)
	9	Ammonia from fuel oil	9	Polyamide (PA)	11	Derivatives from EO for open systems	10	Gasification (HTW process)[a]
	10	Carbon black from fuel oil	10	Polycarbonate (PC)	12	Solvents	11	Hamburg pyrolysis
	11	Steamcracking of ethane/propane/butane	11	Saturated polyester (PET etc.)	13	Derivatives of acetic acid/acetaldehyde	12	BASF pyrolysis (low temperature)
	12	BASF process	12	Unsaturated polyester, alkyd resin	14	Derivatives of toluene, closed systems	13	Hydrogenation (KAB process)

Table 1 (*Continued*)

Secondary fuels module (AB)	Basic chemicals module (BC)		Intermediate product/materials module (CD)		End product module (DE)		Recycling and energy recovery (BTF, BTM, BTP, RU, OXIDAT)	
	12a	Acetylene by partial oxidation	13	Epoxy resin (EP)	15	Derivatives of acetylene	14	Blast furnace
	12b	Methanol from lean gases	14	Phanolic resin (PF)	16	Solid derivatives of paraffins	15	Feedstock recycling of PVC[a]
	13	Ammonia from natural gas	15	Urea resin (UF)	17	Surfactants made of paraffins	16	Energy recovery of pure plastics waste
	14	Acetylene from natural gas (Huels process)	16	Melamine resine (MF)	18	Elektrodes, graphite products	17	Cocombustion of plastics waste in MSWI plants
	15	Synthesis gas from natural gas	17	Polyurethane (PUR)	19	Lubricants	18	Cocombustion of plastics waste in cement kilns
			18	Other plastics	20	Bitumen products		*Rubber waste*
			19	Synthetic rubber (EPDM exclude)	21	Derivatives of ammonia	1	Retreading of waste tyres
			20	Carbon black	22	Others	2	Mechanical recycling of rubber waste
			21	Organochlorine compounds (from EDC)			3	Cocombustion of rubber waste in cement kilns
			22	Other organochlorine compounds (from EDC)			4	Cocombustion of rubber waste in MSWI plants

Table 1 (*Continued*)

Secondary fuels module (AB)	Basic chemicals module (BC)	Intermediate product/materials module (CD)	End product module (DE)	Recycling and energy recovery (BTF, BTM, BTP, RU, OXIDAT)
		23 Ethylene glycol (EG), as antifreeze agent		5 Energy recovery of pure rubber waste in CHP plants
		24 Surfactants from ethylene oxide (EO)		*Waste oil*
		25 Derivatives of ethylene oxide (EO) for open systems		1 Waste oil refineries
		26 Solvents based on acetic acid/acetaldehyde		2 Gasification (SVZ process)
		27 Derivatives of acetic acid/acetaldehyde for open systems		3 Cocombustion of waste oil in cement kilns
		28 Ethanol		4 Energy recovery in power stations and MSWI plants[b]

Table 1 (*Continued*)

Secondary fuels module (AB)	Basic chemicals module (BC)	Intermediate product/materials module (CD)	End product module (DE)	Recycling and energy recovery (BTF, BTM, BTP, RU, OXIDAT)
				Bitumen waste
		29 n-Butanol (as solvent)		
		30 Derivatives of butylene for open systems		1 Hot central-plant recycling of RAP
		31 Toluene and derivatives		2 In-situ asphalt recycling
		32 Xylene as solvent		3 Cold recycling
		33 Derivatives of acetylene		4 Removed asphalt as unbound base and fill
		34 Solid derivatives of paraffins		5 Mechanical recycling of industrial bitumen
		35 Surfactants made of paraffins		6 Cocombustion of industrial bitumen in cement kilns
		36 Elektrodes, graphite products		
		37 Refinery products		
		38 Nitrogen fertilisers/fodder		

Table 1 (*Continued*)

Secondary fuels module (AB)	Basic chemicals module (BC)	Intermediate product/materials module (CD)	End product module (DE)	Recycling and energy recovery (BTF, BTM, BTP, RU, OXIDAT)
		39 Other nitrogen compounds		
		40 Other intermediate products/materials		

[a] No process data are available for this technology.
[b] Use of waste oil as supporting fuel.

returned as post-consumer waste at the end of their lifetime. The post-consumer waste is collected, possibly segregated and pre-treated (module FG). It is then moved on to the waste treatment facilities, i.e. landfilling (module DEP), waste-to-energy facilities or waste water treatment (module OXIDAT) and the various recycling options, i.e. back-to-feedstock recycling (BTF, two types), back-to-monomer recycling (BTM), mechanical recycling (back-to-polymer, BTP) and end product recycling (re-use). Examples of feedstock recycling are the hydrogenation of plastics waste (BTF-A) and the use of plastic waste in blast furnaces and for the production of paraffins (both BTF-B). Glycolysis of polyethylene terephthalate is an example for BTM recycling. Mechanical recycling is mainly applied for thermoplastics and synthetic rubber. An example of end product recycling is the retreading of discarded tyres.

In contrast to post-consumer waste much progress has already been achieved in the recycling and energy recovery of *pre*-consumer waste where there is little scope for further optimisation; moreover the quantities of pre-consumer waste are low compared with post-consumer waste. For these reasons, this study gives most attention to the current and future possibilities of managing *post*-consumer waste.

Recycling and re-use generally require processes tailored to the specific waste stream, and in some cases individual collection schemes are necessary (e.g. for waste bitumen). However, there are also substances which are not recoverable at all, e.g. surfactants; here, the carbon fixed in the product is used dissipatively (not shown in Fig. 1).

For all conversion steps, input–output tables depicting the specific supply and demand relationships in physical terms and the specific energy requirements by types of fuels were elaborated [4]. The data sets include import and export data and, if relevant, the volumes of feedback stream (reflux) and by-products. In the service module (EF), only the delay of material flows is simulated [11], whereas the energy consumption and CO_2 emissions during the use phase are generally not covered. The main reasons are methodological difficulties[4] plus the fact that the research objective would become vague due to the inclusion of all sectors of the economy (since products made of carbon are used practically everywhere).

The data used to simulate the current situation (reference year 1995) reflect the average of all units in operation in Germany (production and recycling processes, MSWI plants etc.). For future projections (chosen year, 2005) a performance equal

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[4] For products consisting of many different materials, the total environmental load (or benefit) must be divided into one part for synthetic carbon materials and another for other materials. Further allocation procedures may be required for the carbon materials. For example, only a part of the plastics used in cars saves weight, whereas the other part contributes to other functions, e.g. comfort and safety. To estimate the benefit of the weight-saving share, the materials substituted must be known (preferably by car component). Analyses of this type are time-consuming, especially if the dynamics over time are taken into account [12]. While this study reveals the potential contribution of an optimised waste management system and the increased production of chemicals from biomass feedstocks, the inclusion of energy consumption and CO_2 emissions during the *use phase* would *additionally* cover all the options of material substitution in end products (e.g. plastics vs. steel vs. aluminium etc.) and their effects on energy use and CO_2 emissions.

to that of the best current commercial technology or of pilot plants in Germany has been assumed.

A submodel has been developed in order to describe electricity generation and steam production [4]. The situation in the chemical industry is assumed to be representative: about two thirds of the electricity required by the manufacturing processes is provided through the public grid; the remainder is supplied from industrial cogeneration units [13].

This study discusses two systems with different boundaries, i.e. the National boundary system and the Total process chain system (Sections 2.1 and 2.2):

2.1. National boundary system

This system is marked by the dotted box in Fig. 1. Only the processes operated within Germany are included in the system. All the material and energy flows are modelled for these processes, whereas all the other sectors of the economy, e.g. households or industrial sectors with no relevance for the system analysed (e.g. non-metallic minerals) are not taken into account (see the broad vertical arrow in Fig. 1). For this reason, the data for module AB only cover the energy input and CO_2 emissions that can be ascribed to non-energy use, i.e. to the input of module BC and to the process energy requirements of all modules of the system. Moreover, as shown in Fig. 1, electricity and heat generated as by-products of waste-to-energy facilities (module OXIDAT) leave the system boundaries; the reason being that the generated electricity is usually supplied to the public grid and the heat is sold on to district heating systems or local industries. For the energy streams leaving the system boundaries a credit, representing the generation from primary resources, is introduced.

2.2. Total process chain system

This includes the entire process chain, starting with resource extraction and ending with the product under consideration. The corresponding energy demand in primary energy terms[5] is called gross energy requirements (GER)[6]. Gross CO_2 emissions are defined by analogy. It is assumed that all the materials required are produced within the system boundaries. Hence, the system analysed may include the processes, which are located abroad. This type of system is also chosen in life-cycle analyses (LCAs) to assess the environmental impacts of competing options for production or waste management. In contrast, accounting for the foreign trade of intermediates would distort the comparison since, e.g. in the case of large net imports, the environmental burden associated with the input manufactured abroad would not be taken into consideration.

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[5] Primary energy refers to the energy resources, e.g. coal, gas and crude oil; in contrast, electricity, for example, is a secondary energy since it has been produced by conversion of primary energy.
[6] Other authors refer to 'gross energy requirements' (GER) as 'cumulative energy demand'.

The total process chain system is chosen to determine the savings of energy and CO_2. Because of this choice

- not all of the savings established might become effective in Germany (since recycling might reduce the demand for *imported* resources or intermediates, i.e. the savings related to energy use and CO_2 emissions occur *abroad* to some extent),
- but all of the savings originate from the more efficient use of fossil resources in Germany.

The National boundary system (Section 2.1) is applied to determine the current energy requirements and CO_2 emissions related to the production and waste management of synthetic organic materials in Germany (data for 1995) and to draw comparisons to other sectors of the German economy (see Sections 3 and 5).

The Total process chain system (Section 2.2) is applied first of all to estimate today's energy use and CO_2 emissions and secondly, to assess the future potentials for reducing the energy input and the release of CO_2. To this end, two strategies are analysed: first, the use of waste as a resource (recycling, re-use, energy recovery) and second, the increased use of biomass feedstock (see Section 4). When determining the potential for savings, a reference case is introduced for the technologies that use waste as a resource. This case describes a standard technology for waste management[7] and thus serves as a baseline to determine the savings. In the case of plastics recycling, for example, the average of all German MSWI plants[8] was adopted as the reference case. This was because as of the year 2005 it will become compulsory in Germany to incinerate all waste with an organic carbon content and direct landfilling will be prohibited (TA Siedlungsabfall).

The so-called product basket-method is used to quantify the net effect of the various technology options relative to the reference case. This is a method to compare processes, which yield different types and quantities of outputs. The main idea behind this method is to ensure comparability by adding the missing outputs; it is assumed that these are produced in the conventional way, i.e. from fossil resources [5,58].

The differences in system boundaries between the concepts described in Section 2.1 and Section 2.2 have to be kept in mind when it comes to comparisons (see below Section 5).
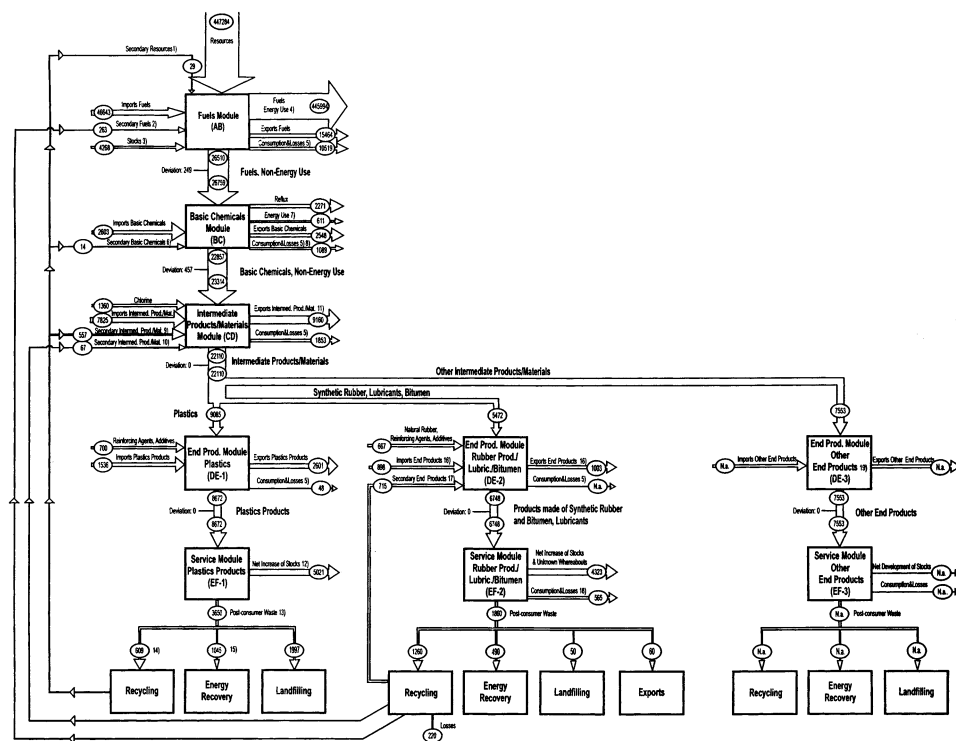
3. Current situation

Fig. 2 shows the material flows by modules in the year 1995. All figures represent physical flows in 1000 Mt (kiloton, kton). The flows presented mainly contain carbon, with smaller amounts of hydrogen, nitrogen, oxygen and chlorine. Most of

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[7] Waste is treated even if it is not used as a resource. Most of it is landfilled or burnt in simple incinerators. These are examples of standard technologies for waste management.
[8] Including the whole range, from simple incinerators to advanced waste-to-energy facilities.

the fuels produced in module AB are consumed in the economy as energy carriers (energy use, 446 Mt) whereas 26.5 Mt is consumed for non-energy purposes. About 1% of this amount is supplied to module AB by BTF recycling of post-consumer lubricants (263 kton) and plastics (29 kton). These plastics are recycled by hydrogenation and in blast furnaces. The figure given for consumption and losses in module AB (10 519 kton) is mainly due to the petroleum refineries' energy requirements.

In module BC, a small amount of basic chemicals was provided by the BASF pyrolysis process (14 kton). In module CD, the recycled materials made from post-consumer plastics (557 kton) and rubber (67 kton) are shown. A considerable share of the recycled plastics was exported in 1995 (342 kton, see Fig. 2).

Fig. 2. Mass flows (in kton) of materials made of fossil carbon in Germany, 1995.
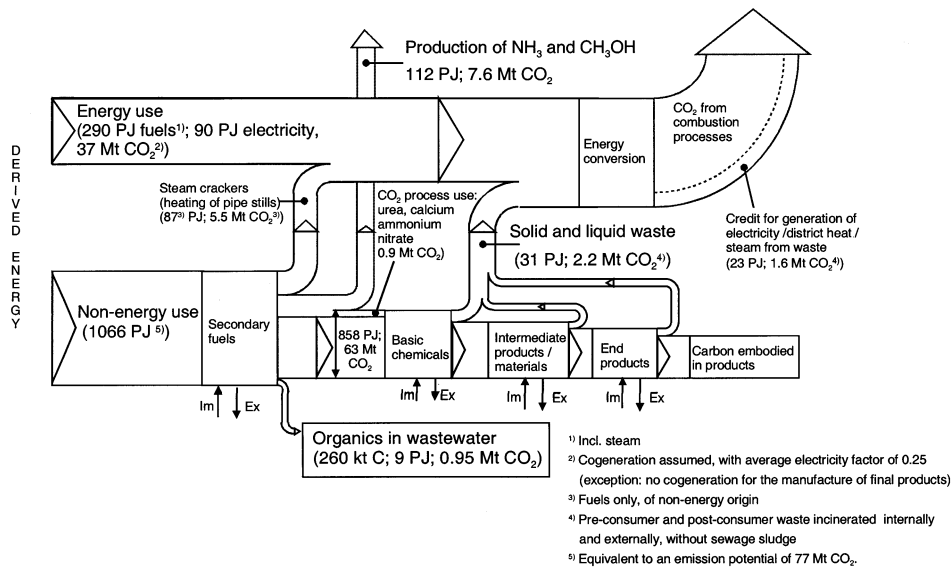
Fig. 3. Interrelation of energy, material flows and CO_2 for the manufacture of virgin synthetic carbon products in Germany, 1995.

Module DE is split into three parts in Fig. 2, one for plastics (module DE-1); another for synthetic rubber, lubricants and bitumen (DE-2); and a third for all other products (DE-3). With regard to the latter, it is practically impossible to follow the imports, exports, domestic consumption and waste management because it contains a multitude of products, most of which cannot be traced in statistical sources.

About 715 kton of post-consumer materials were recycled back to module DE-2. The major part of this flow is bitumen (600 kton) which is recovered as reclaimed asphalt pavement (RAP) and fed back to road construction. Discarded tyres constitute the remaining amount (115 kton) most of which is re-used by retreading.

To summarise, the total amount of materials produced by recycling or re-use corresponds to about 1650 kton (plastics, synthetic rubber, lubricants, bitumen). This is equivalent to 7% of the total domestic consumption of end products made of synthetic organic materials (total output of the entire module DE in 1995, 22 973 kton).

In the petrochemical industry there is a close relationship between energy and materials: part of the feedstock is used as a fuel in the production of the bulk chemicals methanol, ammonia and olefins. Moreover, production waste, which is unsuitable for recycling, is usually incinerated and some of the energy is recovered for steam and electricity generation. Finally, due to imperfect yields, a part of the carbon feed ends up in wastewater and requires treatment. All of these processes lead to immediate CO_2 emissions. The energy and material flows and the CO_2 emissions for virgin material production are shown in Fig. 3. On the left-hand side,

Table 2
Energy requirements and CO_2 emissions related to the manufacture and waste management of synthetic carbon products in Germany, 1995 (National boundary system)[a]

	Material flow[b] (kton)	Consumption of finite primary energy equivalents (PJ)	Fossil CO_2 emissions (kton CO_2)
Fuels module (AB)[c]	26.510	899[d]	4.542[e]
Basic chemicals module (BC)	22.857	258[f]	16.993[g]
Intermediate products/materials module (CD)	22.110	307[h]	19.886[i,j]
End products module (DE)[k]	22.973	175	10.661
Subtotal, primary production	–	1638	52.081
Recycling back to resources/fuels (BTF)	520	1	75
Recycling back to basic chemicals (BTM)	15	0	5
Recycling back to intermediate products/materials (BTP)	624	5	318
Recycling back to end products (RU)	14.815[l]	99	3.262
Incineration (OXIDAT)	1.535	− 35[m]	1.629
Landfilling (DEP)[n]	2.047	0	0
Subtotal, waste management[o]	–	70	5.288
Total, entire system	–	1708	57.369

[a] The table does not provide data for module EF since the energy inputs and CO_2 emissions during the utilisation phase are outside the scope of the analysis. It also does not provide data for module FG since the energy inputs and CO_2 emissions, since transport and logistics have been allocated to the various waste management technologies (modules BTF–DEP).

[b] For the modules describing primary production (AB–DE) the product output used for non-energy purposes is listed; for the modules describing waste management (BTF–DEP) the waste input is listed.

[c] The data given in this line refer exclusively to outputs which are used for non-energy purposes and which are produced from fossil fuels.

[d] Of which 71 PJ as process energy; 828 PJ non-energy use (feedstock) in a narrow sense, i.e. without the fractions used to cover the process energy requirements in the following modules (including these fractions used for process energy, approximately 1070 PJ).

[e] Only CO_2 emissions originating from process energy requirements, i.e. without the CO_2 equivalents of the carbon stored in the products.

[f] Of which 219 PJ originates from feedstocks.

[g] Of which 14 600 kton CO_2 originates from feedstocks.

[h] Of which 20 PJ originates from feedstocks.

[i] Credits for the chemical use of CO_2 have already been taken into account (360 kton CO_2 due to the manufacture of urea resins and melamine resins; 570 kton CO_2 due to the production of nitrogen fertilisers).

[j] Of which 650 kton CO_2 originates from feedstocks.

[k] Consists of three parts, i.e. the final products module for (i) plastics products, (ii) rubber products/lubricants/bitumen products, (iii) other end of products.

[l] Of which 14 700 kton RAP; this is equivalent to 600 kton of bitumen.

[m] The value is negative because credits have been assigned to those amounts of steam and electricity which are co-produced in waste incineration plants. The credit is equivalent to steam/electricity production from primary resources. Credits must be assigned to those flows which leave the system boundary marked in Fig. 1 (please refer to footnote c for different procedure in module AB).

[n] Primary energy requirements and CO_2 emissions due to landfilling are negligible (mainly due to transportation).

[o] Comprises only management of post-consumer waste; treatment of pre-consumer waste is included in the 'subtotal primary production'.

the upper stream represents the direct energy use in the modules AB–DE and the associated emissions of CO_2 (290 PJ fuels, 90 PJ electricity, 37 Mt CO_2), whereas the lower stream represents the non-energy use of fuels, i.e. the input of feedstocks (1066 PJ); of the latter, a total of 239 PJ[9] is oxidised, leading to immediate CO_2 emissions of 16.3 Mt[10]. This demonstrates that the immediate emissions of non-energy origin are by no means negligible and should be included in emission inventories of the chemical industry.

Table 2 gives an overview of the energy inputs and the fossil CO_2 emissions by module. The analysis includes both the uses of fossil resources as feedstocks and as fuels to power the processes in production and waste management. The energy data represent the consumption of finite primary energy. Finite energy is referred to as fossil and nuclear energy. All the data given in Table 2 and Fig. 3 refer to the national boundary system as shown in Fig. 1 (see dotted box). In total, approximately 1700 PJ of finite primary energy was consumed by the system analysed and 57 Mt of fossil CO_2 was released (1995). The subtotals for waste management given in Table 2 are equivalent to 4% of the total primary energy requirements of the system analysed and 9% of the total fossil CO_2 (fuels for transportation of waste are included).

4. Future potentials

Considering the relatively low share of recycling and re-use in 1995 and the large amounts of landfilled post-consumer plastics (see Fig. 2), the question arises as to extent the use of finite energy resources and the release of fossil CO_2 emissions could be reduced either by using waste as a resource or by using biomass as a feedstock.

The net effect of recycling, re-use, energy recovery and the use of biomass can be determined by drawing comparisons to primary or conventional production:

- The options of using waste as a resource are compared with primary production, which is defined as the production from virgin feedstocks and/or fuels. For example, recycled plastics are compared with an equivalent amount of virgin plastics (this is usually less than 100% since it will often be necessary to blend or compound recycled plastics with virgin plastics or to use more recyclates than virgin plastics to achieve the required mechanical properties).
- Secondly, the options of using biomass as a feedstock are compared with conventional production, defined as the production from fossil resources.

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[9] This is the total of the following figures given in Fig. 3: 87 PJ for steam crackers, 112 PJ for NH_3/CH_3OH, 31 PJ for solid and liquid waste and an equivalent of 9 PJ of organics in wastewater.

[10] This is the total of the following figures given in Fig. 3: 5.5 Mt CO_2 from steam crackers; 7.6 Mt CO_2 from NH_3/CH_3OH; 2.2 Mt CO_2 from solid and liquid waste; and 0.95 Mt CO_2 from organics in wastewater. The captive use of CO_2 in urea and calcium ammonium nitrate (0.9 Mt CO_2) is not included in this total since these amounts of CO_2 are inherent in fertilisers and released as a part of agricultural activity, not chemicals production.

Table 3
Achieved and potential savings of gross finite energy requirements (GER) in Germany (product basket-method)

	Reference case	Gross finite energy requirements (PJ)			
		Primary/conventional production in 1995	Savings achieved in 1995[a]	Future potential savings relative to 1995[a]	
				Technology 2005, economy 1995[b]	Technology 2005, economy 2005[b]
Waste as resource					
Plastics (hydrocarbon-based)	Average MSWI plant	745	−26.0[c]	74.1	107.9
Discarded tyres[d]	Cement kiln	43	10.3	16.5	24.3
Technical rubber waste[d]	Landfilling[e]	46[f]	0.0	16.0	21.2
Asphalt	Landfilling	205[g]	29.1	30.0	30.0
Industrial bitumen	Landfilling[e]	36	0.0	11.2	11.2
Waste lubricants	Waste oil refineries[h]	45	2.3	5.4	4.7
Biomass feedstocks					
Bulk chemicals[i]	—	(375)[j]	(0)	(384)	(456)
Oleochemical surfactants[k]	—	23.1	4.8	12.3	12.3
Lubricants from vegetable oils	—	See above[l]	0.9	0.9	4.6
Starch polymers	—	See above[m]	0.1	0.1	1.7
Total (without bulk chemicals)[n]	—	1144	18.1	166.6	218.0

[a] Relative to the reference case (see second column from the left; only for the category 'waste as resource'). In those cases where the technology named as reference case is the only type of process in operation in 1995, the figure in this column is 0.

[b] The term 'economy' refers to the activities of material production and waste use in the year 1995 (second column from the right) and 2005 (first column from the right). Assumed average growth of GDP between 1995 and 2005, 2.3% per year.

[c] The figure is negative because landfilling of plastics waste, which was still the dominating method of disposal in 1995, is a waste of resources relative to energy recovery in an average MSWI plant.

[d] Products made of synthetic and natural rubber, including additives, carbon black etc.

[e] Currently there is no collection and recyling system, so the major part of post-consumer waste is landfilled.

Table 3 (*Continued*)

[f] This figure is subject to considerable uncertainties since both the volume of primary production and the attendant energy requirements (and CO_2 emissions) had to be estimated.

[g] Energy requirements for the production of asphalt.

[h] Status of the technology by the year 1993.

[i] The analysis covers the bulk chemicals ethylene, propylene, butadiene, benzene, toluene and xylene. It is assumed that naphtha steamcrackers are replaced by flash pyrolysis of wood. The brackets indicate that this option will not be feasible for economic reasons in the foreseeable future. Moreover, the use of biomass to produce electricity and steam results in higher savings of fossil CO_2 and is therefore, more favourable from a climate protection aspect.

[j] Steamcracking of naphtha has been assumed as conventional process for the production of bulk chemicals.

[k] These data refer to the year 1996 (data otherwise for 1995).

[l] The conventional production of lubricants has already been entered in this column in the line 'waste lubricants'.

[m] The conventional production of plastics from fossil resources has already been entered in this column in the line 'plastics (hydrocarbon-based)'.

[n] Without bulk chemicals (see footnote i).

Table 4
Achieved and potential savings of gross fossil CO_2 emissions in Germany (product basket-method)

| Reference case | Gross fossil CO_2 emissions (Mt) | | Future potential savings relative to 1995 | |
	Primary/conventional production in 1995	Savings achieved in 1995[a]	Technology 2005, economy 1995[b]	Technology 2005, economy 2005[b]
Waste as resource				
Plastics (hydrocarbon-based) — Average MSWI plant	25.12	4.70	7.00	10.20
Discarded tyres[c] — Cement kiln	2.47	0.75	1.04	1.54
Technical rubber products[c] — Landfilling[d]	2.69[e]	0	−0.09	−0.12
Asphalt — Landfilling	5.69[f]	0.44	0.45	0.45
Industrial bitumen — Landfilling[d]	0.15	0	0	0
Waste lubricants — Waste oil recycling[g]	0.17	0.12	0.23	0.20
Biomass feedstocks[h]				
Bulk chemicals[i] — —	(26.3)[j]	(0.0)	(26.1)	(31.0)[g]
Oleochemical surfactants[k] — —	1.51	0.35	0.87	0.87
Lubricants from vegetable oils — —	See above[l]	0.07	0.07	0.36
Starch polymers — —	See above[m]	0.01	0.01	0.12
Total (without bulk chemicals)[n] — —	37.8	6.2	9.6	13.6

[a] Relative to the reference case (see second column from the left; only for the category 'waste as resource'). In those cases where the technology named as reference case is the only type of process in operation in 1995, the figure in this column is 0.

[b] The term 'economy' refers to the activities of material production and waste use in the year 1995 (second column from the right) and 2005 (first column from the right). Assumed average growth of GDP between 1995 and 2005, 2.3% per year.

[c] Products made of synthetic and natural rubber, including additives, carbon black etc.

Table 4 (*Continued*)

[d] Currently there is no collection and recyling system, so the major part of post-consumer waste is landfilled.

[e] This figure is subject to considerable uncertainties since both the volume of primary production and the attendant energy requirements (and CO_2 emissions) had to be estimated.

[f] CO_2 emissions due to the production of asphalt.

[g] Status of the technology by the year 1993.

[h] All figures listed in this section of the table include the CO_2 equivalents of the fossil carbon stored in the products.

[i] The analysis covers the bulk chemicals ethylene, propylene, butadiene, benzene, toluene and xylene. It is assumed that naphtha steamcrackers are replaced by flash pyrolysis of wood. The brackets indicate that this option will not be feasible for economic reasons in the foreseeable future. Moreover, the use of biomass to produce electricityand steam results in higher savings of fossil CO_2 and is therefore, more favourable from a climate protection aspect.

[j] Steamcracking of naphtha has been assumed as conventional process for the production of bulk chemicals.

[k] These data refer to the year 1996 (data otherwise for 1995).

[l] The conventional production of lubricants has already been entered in this column in the line 'waste lubricants'.

[m] The conventional production of plastics from fossil resources has already been entered in this column in the line 'plastics (hydrocarbon-based)'.

[n] Without bulk chemicals see footnote i).

Tables 3 and 4 present an overview of the results. The options of using waste as a resource (upper block) have been selected by taking into account current and future waste volumes, waste management technologies and legislative developments. The options of using biomass as a feedstock (lower block) fall into two categories: Bio-based bulk chemicals and intermediates could save substantial amounts of fossil resources and CO_2, but their production is not economically viable under current conditions (figures are given in brackets for this reason). In contrast, the other products listed in Tables 3 and 4 are already on the market; oleochemical surfactants have been produced in substantial amounts for some time now, whereas lubricants from vegetable oils and starch polymers emerged more recently and currently represent niche markets.

As described in the methodology section (Section 2), the system chosen for all the comparisons is Section 2.2. For the various options of using waste as a resource, different standard technologies have been chosen as the reference case. In view of German legislation from the year 2005 onwards (TA Siedlungsabfall), the average of all German MSWI plants was adopted as the reference case for plastics recycling. The reference case chosen for discarded tyres is incineration in cement kilns, the dominant process for this type of waste today. In other cases landfilling was selected as the reference, e.g. for RAP where incineration is not possible. For waste lubricants, the recycling technology used in the year 1993 was chosen as the reference.

The energy requirements of primary or conventional production are also given in Table 3 (by analogy, CO_2 emissions in Table 4). The column 'savings achieved in 1995' gives the savings relative to the reference case. In the case of future savings there are two columns, both of which assume the state of technology as will be available from the year 2005 onwards. The two columns differ with regard to the throughput of materials in the economy (year 1995 vs. 2005). For example, the amount of plastics waste will rise between 1995 and 2005 and the saving potentials will increase accordingly [11]. In other cases, it has been assumed in this study that the waste volumes will stagnate (e.g. asphalt), and even a decrease is expected for waste lubricants (own estimates, e.g. based on [14,15]). All the material flows in future are based on the assumption that the GDP will increase by an average of 2.3% per year between 1995 and 2005. The developments of the individual waste volumes and the markets of biomass-derived products are described in detail below. The reduction potentials for energy and CO_2 are also explained.

The use of biomass very often offers the possibility to curtail the use of fossil resources. The use of biomass derivatives as a chemical feedstock is particularly suited to reduce CO_2 emissions if the product is oxidised after use. To make this aspect visible, all CO_2 data referring to biomass use as a feedstock (see lower block in Table 4) include the CO_2 equivalents of the fossil carbon which is fixed in the products[11];

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[11] Hence, the CO_2 equivalents of the fossil carbon fixed in the product (captive use) are included in the entire line, i.e. also in the figures given for conventional production (third column from the left, block 'biomass as feedstock'). Consequently, the data on CO_2 emissions for conventional production, as well as for the savings, are consistent for all the options of using biomass as a feedstock. However, this choice makes the data of conventional production inconsistent with those of primary production for the recycling and energy recovery options (see upper block in Tables 3 and 4) where the fossil CO_2 equivalents of captive use are not included.

in contrast, the figures for the recycling and energy recovery options do not include the fossil CO_2 equivalents of captive carbon use, but only represent the actual emissions released in 1995.

4.1. Post-consumer plastics

The total amount of post-consumer plastic waste is estimated at 3.65 Mt in the year 1995 (without chemical fibres) and 5.3 Mt in 2005 [11]. In 1995, 15% of the entire amount of post-consumer plastic waste was recycled mechanically, 3% was used in feedstock recycling facilities,[12] 27% was incinerated and 55% was landfilled. The figures for the year 2005 are based on a scenario [11] which assumes that 36% of the waste is recycled mechanically, 32% processed in feedstock recycling plants, and the remaining 32% fed to advanced waste-to-energy facilities. In the case of mechanical recycling, energy and CO_2 savings vary, depending on whether virgin polymers are substituted (22% of the waste in 2005) or other materials — mainly wood, concrete and iron — are replaced (14% of the waste in 2005). According to Table 3 the savings in gross energy achieved in 1995 are negative (relative to the reference case, i.e. MSWI plants). This is due to the fact that landfilling, which accounts for a substantial share of waste (55% in 1995) does not recover the energy contained in plastic waste (heating value). In contrast, landfilling of plastics waste causes practically no CO_2 emissions in the short term, and thus the CO_2 savings achieved in 1995 are positive.[13] For further details reference is made to own work in the field [4,11,58].

4.2. Discarded tyres

This study estimates the total amount of discarded tyres at 600 kton in 1995 (own estimate based on [16,17]; personal communication with P. Krieg, Tyre Recycling & Produkt GmbH, 27.8.1998) and at 885 kton in 2005 (own estimate based on personal communication with H. Hirsch, Gesellschaft für Altgummi-Verwertungssysteme, 31.8.1998). The breakdown of the waste management processes is given in Table 5. Similar to what is planned for plastic waste, landfilling of discarded tyres will also be prohibited from the year 2005 onwards. Further development of retreading processes depends to a large extent on the acceptance level of private consumers [16]. Recycling of discarded tyres — and waste rubber in general — might grow considerably in the future, especially if the recently promising developments of devulcanising rubber waste ultimately prove to be a success [18–20]. Most of the savings given in Tables 3 and 4 are originated from

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[12] The amount fed to feedstock recycling facilities has more than tripled between 1995 and 1997.

[13] However, these CO_2 emissions could be released in the long term; in this case the environmental burden is simply shifted to the future.

Table 5
Recycling and incineration of discarded tyres in Germany in the years 1995 and 2005 (own estimates based on [56] and various other sources; compare [4])

	Re-use, recycling and incineration			
	1995		2005	
	(kton)	(%)	(kton)	(%)
Retreading	100	17	170	19
Other types of product recycling	15	3	15	2
Mechanical recycling	67	11	160	18
Cement kilns	217	36	350	40
Other types of incineration[a]	65	11	190	21
Landfilling	35	6	0	0
Exports	60	10	0	0
Unknown	40	7	0	0
Total	599	100	885	100

[a] Incineration in municipal waste incineration plants and CHP plants fuelled with discarded tyres.

retreading (energy saved, ca. 80 GJ/ton waste; CO_2 saved, ca. 6.0 ton CO_2 per ton waste) and mechanical recycling (energy saved, ca. 55 GJ/ton waste; CO_2 saved, ca. 3.5 ton CO_2 per ton waste; all figures are relative to incineration in a cement kiln which is the reference case) [4].

4.3. Technical rubber waste

Compared with the figures for discarded tyres, the estimates given in Tables 3 and 4 for technical rubber waste are less certain. The reason for this is the lack of a comprehensive inventory of production and waste management for technical rubber products. It is estimated that total post-consumer waste will increase from 400–450 kton in 1995 (own estimate based on personal communication with Willing, German Federal Environmental Agency, UBA, 7.9.1998; personal communication with Krieg, Tyre Recycling & Product GmbH, 27.8.1998; [17]) to 500–650 kton by the year 2005 (own estimate based on personal communication with Willing, German Federal Environmental Agency, UBA, 7.9.1998). It is expected that only about 5% will be recycled mechanically while the rest will be incinerated, mainly in MSWI plants and cement kilns. This enables indisputable energy savings (see Table 3), which mostly originate from mechanical recycling (energy saved, ca. 85 GJ/ton waste) and from energy recovery in advanced waste-to-energy facilities (in the range of 40 GJ/ton waste; all figures relative to landfilling which is the reference case) [4]. In total, the CO_2 emissions remain practically unchanged (see Table 4) although advanced waste-to-energy facilities have been assumed for the year 2005; the reason being that, even in these highly efficient plants, the production of steam and electricity leads to more fossil CO_2 than modern power plants or cogeneration units; this compensates for the savings made by mechanical recycling [4].

4.4. Recycling of asphalt

Asphalt recycling processes can be divided into two major methods, hot recycling and cold recycling [21]. Reclaimed asphalt pavement (RAP) can also be used as an unbound base and fill [21]. Generally, the final engineering properties of hot-mix asphalt (HMA) are higher than those achieved by cold-mix technologies [22]. This results in the following list of processes (which has been ordered according to the declining quality of recycling) [21]:

- Hot, central-plant recycling. The old pavement material, which has been removed, is transported to a plant where it is mixed with new bitumen and virgin aggregates. The share of RAP is usually around 30%; at most, recycling percentages of 50–70% are achieved, depending on the quality requirements of the mix and the properties of the old asphalt [21,23,24].
- In-situ asphalt recycling. This is a new technology for heating and removing 5–10 cm of the top road layer; mixing it with virgin materials and then applying it directly as the final asphalt layer, ('asphalt recycling travelplant') [21,23,24].
- Cold recycling, either in-situ or in central plants. Two types of binders, foamed bitumen and bitumen emulsion, are used without the application of heat [21,23–25].
- Finally, removed asphalt can be used as unbound base and fill, mainly for road construction [21,24].

In 1995, 12 Mt of RAP were processed by hot, central-plant recycling (personal communication with Els, Deutscher Asphaltverband, DAV, 14.9.1998). This is equivalent to savings of 500–700 kton of virgin bitumen.[14] An additional 3 Mt of RAP was used as unbound base and fill (fourth option; personal communication with Els, see above). A share of 2% of used asphalt was landfilled (personal communication with Els, see above). Almost all the energy and CO_2 savings given in Tables 3 and 4 are resulted from the hot-mix process. For the short-term future, it is expected that the total amount of RAP will remain about the same since the intensity of road repairs will remain at a level similar to 1995 (own estimate based on personal communication with Höltken, Arbeitsgemeinschaft der Bitumen-Industrie, ARBIT, 11.9.1998). Moreover, it has been assumed in the calculations that use as unbound base and fill will practically disappear in favour of hot processes and cold recycling.

4.5. Recycling of industrial bitumen

Industrial bitumen is mainly used for the manufacture of roofing felts. It is estimated that about 300 kton of bitumen waste is generated from this source every year (own estimate based on various sources; compare [4]). It is expected that the volume of waste will remain more or less constant up to the year 2005 (own estimate based on personal communication with Höltken, Arbeitsgemeinschaft der

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[14] Asphalt is produced by mixing 4–8% bitumen with 92–96% mineral materials.

Bitumen-Industrie, ARBIT, 11.9.1998). At present, most of the industrial bitumen waste is landfilled (due to the low costs); smaller fractions are incinerated in cement kilns (energy recovery) or recycled as building materials (e.g. for joint fillers, building protective matting and silencing matting) and asphalt (used for deeper pavement layers; compare [26]). Since organic material landfilling will be prohibited from the year 2005 onwards, it has been assumed in this study that 50% of all industrial bitumen waste will be fed to cement kilns and the remainder will be recovered for building materials in 2005. The energy savings given in Table 3 are based on specific savings of about 42 GJ/ton waste for incineration in cement kilns and 33 GJ/ton waste for recycling (all figures are relative to landfilling which is the reference case) [4]. No CO_2 savings are achieved by this combination of processes (see Table 4).

4.6. Waste lubricants

The total amount of waste lubricants in 1995 is estimated at about 1260 kton, but only 690 kton are recovered after use (personal communication with K. Fricke, German Federal Environmental Agency, UBA, 2.12.1998), whereas the rest is lost due to cocombustion in engines (165 kton) [27], product use in mostly dissipative applications (130 kton, e.g. vaseline and anti-corrosives) [27] or other losses and leakage (270 kton) [27]. Of the amount recovered, about 480 kton[15] were fed to waste oil refineries, 170 kton incinerated in cement kilns and 40 kton gasified in the SVZ plant[16] (personal communication with K. Fricke, German Federal Environmental Agency, UBA, 2.12.1998). It is expected that the domestic consumption of lubricants will decline in future.[17] Accordingly, it has been estimated in this study that the amount of waste lubricants available for recovery will decrease from 690 to about 600 kton by the year 2005 (own estimate based on various sources, e.g. [15]). The figures given in Tables 3 and 4 are based on the assumption that 50% of all waste lubricants will be recovered in waste oil refineries, 40% in cement kilns and most of the remaining 10% will be gasified. The energy savings are achieved mainly from cement kilns (10.9 GJ/ton waste) and advanced waste oil refineries (6.6 GJ/ton waste), whereas virtually all the CO_2 savings are achieved from cement kilns (0.8 ton CO_2 per ton waste; all figures are relative to an average waste oil refinery in Germany in 1993 which has been chosen as the reference case) [4].

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[15] Water content included.

[16] SVZ (Sekundärrohstoffverwertungszentrum) is a company operating a solid bed gasification process in Schwarze Pumpe, Germany. In 1995, the entire production of synthesis gas in the SVZ plant was fed to a congeneration unit. Since 1997, 60% of the synthesis generated is converted to methanol and the rest is fed to the cogeneration unit (compare Section 3).

[17] Due to improved engine technology, the monitored demand for oil change and new technologies for saving or avoiding the use of lubricants in metal cutting.

4.7. Bulk chemicals from biomass

Many organic chemicals can be produced from biomass feedstocks instead of from fossil resources (see e.g. [28]). To obtain an impression of the potentials and the difficulties involved a group of bulk chemicals, consisting of olefins (ethylene, propylene and butadiene) and aromatics (benzene, toluene and xylene), has been studied [4,29]. A comparison was made between three processes used to manufacture these bulk chemicals from biomass. These are high temperature flash-pyrolysis of wood, dehydration and the methanol-to-olefins (MTO) process. The technologies differ in terms of development status, prospects, energy consumption and yields. The highest yields of organic chemicals are achieved from flash-pyrolysis of wood, but so far the viability of this process has not been proven on a larger scale. Nevertheless, to determine the maximum saving potential, flash-pyrolysis has been chosen for further analysis. It is assumed that the total German production of olefins and aromatics in naphtha steamcrackers (6.2 Mt in 1995) [30] is produced by this technology. As Table 3 shows, the savings of finite energy and fossil CO_2 achieved by flash pyrolysis of wood are comparable with the respective inputs to naphtha steamcrackers (primary production). The reason is that the steam and electricity requirements of the flash pyrolysis process are covered by a fraction of the pyrolysis gas, which is generated from the biomass feedstock. As mentioned earlier, the CO_2 data in Table 4 include the fossil carbon inherent in the products. It is assumed that the demand for the bulk chemicals analysed will increase by 2.3% p.a. between 1995 and 2005.[18]

According to Tables 3 and 4, production of the bulk chemicals in the year 1995 would involve a land use of 20 000 km^2, representing about 12% of the total arable land in Germany. If the production of bulk chemicals from *all* steamcrackers (including those operated on gas oil and light hydrocarbons) were added, then the land use requirements would increase by about 40%.

4.8. Oleochemical surfactants

Surfactants (surface-active agents) can be derived from both petrochemical feedstocks and vegetable oils (oleochemical surfactants). In the mid and late 1990s, about one third of the total surfactant production in Germany was based on biomass-derived raw materials and two thirds originate from fossil resources [31]. Shortly after they are used, surfactants are degraded and the fixed carbon is oxidised to CO_2. Whether these emissions are relevant to climate change depends on whether the CO_2 released is of fossil or non-fossil origin. CO_2 related to process energy requirements must also be taken into account. Table 4 shows the results of these calculations: if the most important fossil surfactants produced in Germany

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[18] This assumption is plausible since most of the bulk chemicals analysed (ethylene, propylene, butadiene, benzene, toluene, xylene) are used to a considerable extent for plastics production; the ratio of plastics production over GDP (measured in ton over Deutsch mark) increased considerably in the past, but now seems to be stabilising.

(215 kton in 1996[19]) were replaced by their oleochemical counterparts made from coconut oil (CNO) then fossil CO_2 emissions would decline by 0.52 Mt [31]. This is equivalent to a 34% reduction compared with 1996.[20] For finite energy (Table 3) the calculations yield a comparable percentage (32%). These figures are an overestimation of the available emission reduction potential according to the current state of art. However, it is assumed in this study that this can be achieved by the year 2005. Relatively high savings — both for finite energy and fossil CO_2 — were already achieved in 1996 (see Tables 3 and 4) [31,32]. It has been assumed in this study that the production of surfactants will remain constant between 1995 and 2005.[21]

4.9. Lubricants from vegetable oils

In 1995, lubricants made from vegetable oils (mainly rape-seed oil) accounted for about 30 kton, which is the equivalent of less than 3% of the total lubricants market in Germany (1.14 Mt). Projections for the future range from about 100 kton [33] up to 700 kton [34]. In this study, it is assumed that 150 kton of lubricants, i.e. 15% of the total lubricants market, will be produced from vegetable oils by the year 2005 (compare [35,36]).

In principle, there are two types of bio-based lubricants; i.e. natural esters (triglycerides) and synthetic esters derived from vegetable oils. Natural esters are comparatively simple to produce. However, the material properties of natural esters are inferior to those of synthetic esters (especially due to ageing). Therefore, to be on the safe side, an important lubricant belonging to the group of synthetic esters has been chosen for the calculations presented in Tables 3 and 4: this is a polyol ester synthesised from trimethylolpropane (TMP) and rape-seed fatty acid. Compared with a petrochemical lubricant, the savings related to the TMP ester are 31 GJ non-renewable energy per tonne of lubricant and about 2.4 ton CO_2 per ton [4].

4.10. Starch polymers

Over the past few years an increasing number of plastics made from biomass feedstocks have entered the market, e.g. starch polymers, polylactides, polyurethanes[22], polyhydroxyalkanoates[23] (PHA) and plastics reinforced with natu-

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[19] The following surfactants are included in this total, LAS; SAS; AS-Pc; AE_3S-Pc; AE_3-Pc; and AE_7-Pc (Pc stands for 'petrochemical').

[20] In contrast to the other options analysed the reference year chosen for surfactants is 1996, not 1995.

[21] This is a conservative assumption compared with other projections, which assume an increase in the range of 2% p.a. (e.g. [37] for Western Europe). Considering the maturity of the sector and the market in Germany, it was considered appropriate to make this cautious assumption.

[22] Only the polyol components are synthesised from biomass feedstocks. Research is under way to produce the isocyanate component from non-fossil resources too [39].

[23] The main representatives are polyhydroxybutyrate (PHB) and polyhydroxyvalerate (PHV).

ral fibres. On the other hand, some of the classic biomass-derived plastics are losing their share in the market, e.g. regenerated cellulose. It is impossible to make a general statement about whether plastics from biomass are favourable in terms of energy use and CO_2 emissions compared with petrochemical polymers. For example, the gross energy requirements for PHA are currently higher than for polyolefins; this is due to the complicated production process of PHA [4,38]. Research and development is under way to optimise the process and this should reduce the energy input. On the other hand, starch polymers, which are available both with and without petrochemical co-polymers[24], already offer a potential to save energy and curtail fossil CO_2 emissions [4,38]. Depending on the share of petrochemical co-polymers, starch polymers offer saving potentials relative to polyethylene in the range 12–40 GJ/ton plastic and 0.8–3.2 ton CO_2 per ton plastic. However, the inferior material properties of starch polymers, especially their sensitivity to moisture, limit their market potential. For most of the other, new biomass-derived plastics, no process or LCI data have been published so far. It is for this reason that only starch polymers are included in Tables 3 and 4. In 1995, starch polymers accounted for about 5 kton and 80% of the entire production of bio-based polymers. It is assumed that the share of starch polymers will increase up to 70 kton by the year 2005.[25] This is considered to be a moderate, yet positive development. In the event of unfavourable conditions, a market volume of only 20–30 kton is expected, whereas a booming demand would result in a market growth up to 100–150 kton (personal communication with Dr S. Facco, Novamont GmbH, Eschborn). The savings of energy and CO_2 in absolute terms are exceeded by all the other options studied (compare Tables 3 and 4) since the assumed production volume of starch polymers by 2005 is very small (for comparison, total plastics manufactured was 10.4 Mt in 1995).

5. Discussion

The analysis showed that the finite primary energy input related to non-energy use within Germany's national boundaries measured approximately 1700 PJ in 1995 (see Table 2). This figure includes the feedstock, the entire chain of production and waste management. Total fossil CO_2 emissions released from this system amount to 57 Mt. If compared with the entire industrial sector in Germany (without non-energy use[26]) the share is 44% for energy and 20% for CO_2. The respective percentages

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[24] The most prominent representatives are combinations of thermoplastic starch with polyvinylalcohol and polycaprolactone. Pure thermoplastic starch is also marketed. Blends of thermoplastic starch with polyolefins have not been taken into account in Tables 3 and 4 since they are not fully biodegradable (this is considered to be an important marketing aspect).

[25] The shares of the various types are:in 1995, 20% pure thermoplastic starch (TPS); 10% starch/polyvinylalcohol (85/15%); 70% starch/polycaprolactone (47.5/52.5%);in 2005, 20% pure thermoplastic starch (TPS); 15% starch/polyvinylalcohol (85/15%); 65% starch/polycaprolactone (47.5/52.5%).

[26] For the energy requirements and CO_2 emissions of the entire industrial sector in Germany, see footnote c in Table 6.

relative to the total German economy[27] are 12% for energy and 6% for CO_2. The higher percentage for energy results from the use of fossil fuels as a feedstock, fuels equivalent to about 830 PJ were fixed in synthetic organic products, part of them for many years or even decades. Another 239 PJ, also of non-energy origin, were oxidised immediately during the production process, resulting in 16.3 Mt of fossil CO_2. These emissions are often overlooked in national emission inventories.

The above products, for which the potential for recycling, recovery and bio-based feedstocks has been assessed, represent about two thirds of the total production of materials of non-energy use in Germany.

According to Tables 3 and 4 the production of bulk chemicals from biomass feedstocks offers the highest potential for energy saving and CO_2 mitigation. However, flash pyrolysis of wood for the production of olefins and aromatics has only been demonstrated on the laboratory scale and this technology is not expected to be economically competitive in the foreseeable future. Moreover, the gasification of woody biomass and subsequent generation of electricity results in higher savings of CO_2 [29], and so this would be the preferred option within a carbon abatement strategy. For these reasons, the possibility of producing bulk chemicals by way of flash pyrolysis will not be followed up in this assessment. Hence, this option is not included in the totals given in Tables 3 and 4.

It should be noted that only one technology has been chosen as the reference case (e.g. incineration in an average MSWI plant). If, in reality, further practices are in use for one type of waste, the calculation usually yields savings even for 1995 (see Tables 3 and 4, third column from the right; the figures for 1995 are relative to the reference case).

As mentioned earlier, while not all of the savings identified occur in Germany they all originate from measures taken in Germany. Keeping the different system boundaries in mind, it is possible to compare the totals according to Tables 3 and 4 with the 1995 figures given in Table 2[28]. The result is shown in Table 6 in the lines 'total savings/total system' (separate lines for energy and CO_2): a maximum of 12.8% of energy and 23.8% of CO_2 can be saved. It may seem quite remarkable that the saving potential for energy (12.8%) is much smaller than that for CO_2 (23.8%); the reason is that for energy, the reference quantity ('total system') includes the entire non-energy use.

The reason for the low percentage of recycled and re-used synthetic organic materials is that considerable amounts of waste are landfilled and incinerated and, more importantly, that there is a large increase in stocks. For example, in the case of plastics, the increase of stocks represents 58% of the consumption of end

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[27] Primary energy requirements of the total German economy equalled 14 300 PJ in 1995, in total, 895 Mt of fossil CO_2 were emitted [40].

[28] There is no straightforward way for harmonising the two approaches. Both the calculation of the saving potential following the National boundary system Section 2.1 and the calculation of the total system's energy requirements and CO emissions in 1995 according to the Total process chain system Section 2.2 would require several assumptions resulting in uncertainties.

products (see Fig. 2). This is due to the large share of plastics used in long-lived products: it has been estimated for Germany that about 70% of the total consumption of plastics products are in use for more than 3 years and about 30% for more than 11 years [11]. The large increase of stocks (accumulation) is the main reason why the ratio of savings to the values of primary/conventional production is particularly low for some of the types of materials listed in Tables 3 and 4. Since

Table 6
Gross energy and gross CO_2 savings presented in perspective

	Achieved savings in 1995	Future potential savings relative to 1995	
		Technology 2005, economy 1995[e]	Technology 2005, economy 2005[e]
Energy			
Total savings[a] (PJ)	18.1	166.6	218.0
Ratio (total savings/total system 1995[b])	1.1%	9.8%	12.8%
Ratio (total savings/total German industry 1995[c])	0.5%	4.3%	5.6%
Ratio (total savings/total German economy 1995[d])	0.1%	1.2%	1.5%
CO_2			
Total savings[a] (Mt CO_2)	6.2	9.6	13.6
Ratio (total savings/total system 1995[b])	10.9%	16.7%	23.8%
Ratio (total savings/total German industry 1995[c])	2.2%	3.3%	4.7%
Ratio (total savings/total German economy 1995[d])	0.7%	1.1%	1.5%

[a] See Tables 3 and 4, bottom line (total without bulk chemicals).

[b] 'Total system' gives the primary energy equivalents/fossil CO_2 emissions of the entire system analysed in this study, i.e. the total covering all the modules AB–DEP. The figures are given in the bottom line of Table 2.

[c] 'Total German industry', this is the total primary energy use/the total fossil CO_2 emissions in Germany in 1995, including the entire productive sector, coking plants and the refinery sector: 3900 PJ, 290 Mt CO_2. The figures include the energy and CO_2 equivalents of electricity use. Non-energy use is excluded since it is usually not allocated to the industrial sector in inventories on energy and CO_2. The energy figure has been estimated on the basis of [57]; the CO_2 figure has been estimated on the basis of [57,40], including 27 Mt CO_2 from the industrial processes [40]. This is the only comparison where the percentage for energy is larger than that for CO_2. The exclusion of non-energy use and the inclusion of CO_2 from 'industrial processes' are the reasons.

[d] 'Total German economy', this is the primary energy use/the fossil CO_2 emissions of the German economy in 1995: 14 300 PJ, 895 Mt CO_2 [40]. The figures for the total German economy include the contribution from non-energy use, which is however, relatively small. Therefore, the figures for the total German economy are dominated by the energy system and its immediate conversion of energy to CO_2. The total saving potential on the non-energy side (218 PJ energy and 13.6 Mt CO_2) well reflects the energy to CO_2 ratio in the country's energy system.

[e] The term 'economy' refers to the activities of material production and waste use in the year 1995 (second column from the right) and 2005 (first column from the right). Assumed average growth of GDP between 1995 and 2005, 2.3% per year.

direct landfilling of organic carbon content waste will be prohibited in Germany from the year 2005 onwards, and since the material flows in the economy will gradually reach a steady state, the amounts available for recycling and re-use will increase in the future. The potential is very high in the long term. Two reasons can be given for this. First, the amount of post-consumer plastics waste, being the largest stream of the materials studied, would increase by a factor of 2.4 [11] if there was no net increase in stocks (based on data for 1995 according to Fig. 2.[29]) And second, the use of some materials — again especially plastics — will continue to rise in the future, and this too will result in larger amounts of waste.

When calculating the potential of future savings, a plausible mix of technologies was assumed; for example, in the case of discarded tyres, the saving potential was determined on the basis of a combination of retreading, mechanical recycling and incineration (see Table 5). In nearly all the cases, the technologies assumed are already commercially available; in the remaining cases the assumed technology could be available by the year 2005. Hence, the future data given in Tables 3 and 4 represent the *technical potential by the year 2005*.

However, the complete diffusion of these technologies, i.e. introduction at all relevant sites, will require additional time (possibly another 10–20 years under current conditions). In addition, a commercially available technology will probably not be implemented, despite the fact that it can save energy, if the net economic effect is not a positive one. These aspects are taken into account in the so-called *economic potential* for saving energy resources or mitigating CO_2 emissions [9]. We may expect only a part of the economic potential to be realised in practice. This part is given by the so-called *market potential*, which determine the investment decision criteria applied by investors under prevailing market conditions [9]. Neither the economic potential nor the market potential has been studied in this study.

There are other opportunities available for reducing the consumption of finite energy and curbing fossil CO_2 emissions, which have not been discussed in this study. Examples are the application of traditional measures to improve energy efficiency (e.g. by improved heat exchange or optimised separation processes) and the introduction of advanced designs, new processes or catalysts enabling higher yields in conventional production.[30] The options of using renewable energies to cover (parts of) the process energy requirements were also excluded from this analysis.

In the following, the various assumptions are assigned to three categories, the first category comprises assumptions which are not expected to cause a bias of the

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[29] The domestic consumption of virgin petrochemical plastics equalled 8.7 Mt in 1995, whereas the total waste available for recycling/recovery amounted to 3.65 Mt in the same year (excluding chemical fibres); this gives a factor of 2.4.

[30] In the German project report [4] the saving potential of 12 innovative processes for the manufacture of synthetic organic intermediates from petrochemical feedstocks has been estimated (e.g. vinyl chloride, propylene oxide, ethylene oxide). The inclusion of these processes increases the saving potential for CO_2 by 3%, i.e. from 24 to 27% (ratio, total savings/total system 1995, see Table 6).

results, or on which there is too little information available to draw qualitative conclusions about the uncertainties; the second category lists those assumptions that could lead to an overestimation of the saving potentials; and finally, the third category contains the assumptions that could lead to underestimation.

1. The following assumptions and methods are considered to be neutral in terms of the results, or their impact cannot be assessed because of the lack of more detailed information:

   ○ In many cases the calculations rely on grey or unpublished literature and personal communication with experts. This refers in part to the production volumes (both of products made from biomass feedstocks and from recycling) and partly to the data on process energy requirements. In general, somewhat conservative estimates were made wherever the uncertainties were obvious, e.g. for the future production volumes of starch polymers and lubricants from vegetable oils.

   ○ The saving potentials identified in the areas of recycling and biomass use (see Tables 3 and 4) are generally not additive, i.e. they each exclude the other to some extent: most importantly, not all of the recycling technologies for petrochemical plastics are easy to apply for bio-based plastics (e.g. hydrogenation). However, the assumed production volumes of bio-based plastics are still comparatively small (less than 0.3% of the total non-energy use), so the effect of double counting is negligible.

   ○ It is a well-known fact that important changes have taken place in plastics recycling since 1995 (reference year of this analysis). When this study was prepared, the latest set of reliable data originated from the year 1997. In 1997 the amount of secondary resources produced by BTF recycling had increased to about 130 kton (29 kton in 1995). This was due to the increased amounts of plastic waste fed to the hydrogenation and the blast furnace process, and the start-up of a demonstration plant to produce paraffins from plastics (PARAK process). While in the case of BTM recycling the BASF pilot plant for pyrolysis had been closed down (− 14 kton) about 90 kton of plastics waste and 40 kton of waste lubricants was gasified in the SVZ[31] plant, and 60% of the synthesis gas generated was converted to methanol (the rest being fed to a cogeneration unit). Whereas the mechanical recycling for domestic use remained more or less constant between 1995 and 1997, the total amount of agglomerates and waste exported for recycling decreased in that period [4]. To summarise, although plastics recycling continued to increase between 1995 and 1997, recycled and re-used synthetic organic materials still accounted for less than 10% of the total amount of the end products consumed domestically in 1997.[32]

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[31] SVZ (Sekundärrohstoffverwertungszentrum) is a company, which operates a solid bed gasification process in Schwarze Pumpe, Germany.

[32] It might be thought inappropriate to choose the total amount of the end products consumed domestically as the reference quantity. The reason for doing this is that recycling/re-use is not possible for many of the products covered in the 'other end products module' in Fig. 2 since the materials are used in a dissipative way in these applications (e.g. surfactants). If the 'other end products' are excluded (i.e. if the reference quantity only consists of plastics and rubber products, lubricants and bitumen) the percentage increases by about 50%. Hence the percentage recycled and re-used is still close to 10%.

2. The following assumptions contribute to the overestimation of the saving potentials:
   ○ There is some uncertainty as to the total amount of post-consumer plastic waste since this has not been surveyed. The value will be higher or lower depending on whether the total amount has been determined by using a top-down or a bottom-up approach [11]. The amounts assumed for this analysis are somewhat on the high side. Further analysis is needed to refine the two methods.
   ○ For oleochemical surfactants it was assumed that the most important petrochemical surfactants produced at present in Germany will be replaced by their oleochemical counterparts. While this is an overestimation of today's technical potential, it could be achieved in the near future if the necessary efforts are made in research and development.
   ○ It has been assumed for all processes using bio-based feedstocks that the biomass is produced in a sustainable fashion. This implies that the energy produced from biomass sources is infinite and that CO_2 originating from bio-based sources is recaptured in plant growth (i.e. there are no net CO_2 emissions apart from the fossil fuels used in the process chain, e.g. for tractors and fertilisers). However, there are also examples of unsustainable agriculture, which have not been taken into account in the calculations presented in this study. If they were taken into consideration, the savings of energy and CO_2 might decline to some extent.
3. The following assumptions contribute to the underestimation of the saving potentials:
   ○ The list of options studied in order to identify the total savings potential is bound to be incomplete. For example, neither the recycling and the re-use of chemical fibres nor the manufacture of biomass-derived plastics other than starch polymers and PHA has been studied. In addition, the material flows were only studied in detail for plastics, synthetic rubber, lubricants and bitumen. There is, however, a multitude of other synthetic organic materials that cannot be traced in statistical sources as pure substances since they are combined with other materials to form end products (see 'other end products' in Section 3 and Fig. 2). This remaining group comprises certain products, which can be recycled and re-used, and in some cases processes are even in operation, e.g. for solvents and degreasing agents. These processes were excluded from the further analysis since there were no reliable data available; this could lead to a relatively small underestimation of the total potential presented in this study since the quantities recycled and re-used are generally small. Innovations on which there are no reliable data available at the moment, but which are likely to undergo substantial progress up to the year 2005 (e.g. devulcanisation of post-consumer rubber), have also not been taken into account. Further saving potentials that might be achievable through material substitution, both within the system investigated and by

replacement of other materials, have not been analysed[33] and are therefore not included in the estimates of the saving potentials.All in all, the aspect of incompleteness could add up to a considerable level of underestimation.

○ Only the savings achieved from recycling in the first cycle have been identified. The real savings potential is higher if the materials are not only recycled once, but twice or even three times, i.e. if a strategy of quality cascading is pursued. Feasibility depends mainly on the quality of waste, the efforts in separation and purification and the actual application of the recycled material.

○ It has been assumed that surfactant production will stagnate until 2005; this is a conservative assumption, if compared with the expectations found in the literature (e.g. [37]; also see footnote in Section 4.8).

○ The amount of waste lubricants estimated for the future may be on the small side; on the basis of available information it would also be justified to assume a standstill as opposed to a decline in the amounts of waste.

○ A high quality product (TMP ester) has been assumed for lubricants from vegetable oils; it is more energy intensive to produce this lubricant compared with natural esters (these represent other potential substitutes for petrochemical lubricants).

An attempt was made to quantify the uncertainty ranges by module. These range from -50 to $+25\%$ for the material flows, and from -20 to $+30\%$ for the energy data and CO_2 emissions [4]. On this basis it was estimated that for the majority of all cases (85%) the uncertainty of the energy data and CO_2 emissions is [4]:

● $\pm 15\%$ for the reference year 1995;
● $\pm 30\%$ for the year 2005.

If the latter uncertainty range is applied to the ratio 'total savings/total system 1995' in the case 'technology 2005, economy 2005' (see Table 6) the range of saving potentials (in 85% of all cases) is:

● 9–17% for energy and;
● 17–31% for CO_2.

As a general limitation, this study focuses only on energy and CO_2 emissions. To draw conclusions related to the issue of global warming, other GHGs would also have to be analysed. This would go beyond the scope of this study. Moreover, this study does not permit any conclusions to be drawn on the environmental impacts in general; this can only be done on the basis of comprehensive LCAs.

According to Tables 3 and 4, most of the saving potential available in the short term can be mobilised by using synthetic organic waste as a resource (199 PJ and 12.3 Mt CO_2 in total), and not by using biomass as a chemical feedstock.

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[33] There is one exception, which is the use of recycled plastics as substitutes for wood, concrete and steel; this has indeed been taken into account (also see [58]). However, there are many other possibilities for substitution which have not been analysed, e.g. the use of (virgin) plastics to replace glass, steel and aluminium in the packaging and automotive sector.

Now-a-days recycling and the re-use of carbon materials is faced with two main problems:

- First, for many materials the generation of waste is still small when compared with consumption (no steady state and net exports). There is a very large net increase of stocks in the economy[34] (see Fig. 2, modules EF) and there is a long retention time of the materials in society (e.g. asphalt, piping and window frames in buildings; compare [11]);
- Second, recycling is still not economical for many types of waste; the main reasons being the abundance of low-priced virgin products[35] and the large amount of different materials and lightweight items in the waste stream (high entropy) [41]. This generally results in high costs for recycling logistics[36], sorting and recycling processes since these usually have to be tailored specifically to the type of waste.

However, the fact that the amount of waste will continue to rise for most synthetic organic materials will motivate the development of waste management strategies and effective technologies (which should also give due consideration to recycling and re-use). For the near future, policy pursued in Germany is to prohibit landfilling of materials containing organic carbon (TA Siedlungsabfall). As a consequence, the major part of this waste will be incinerated from the year 2005 onwards. Compared with landfilling this will save fossil fuel resources. However, if the *average* efficiency of all MSWI plants fails to increase compared with today, then CO_2 emissions are very likely to rise. High priority should therefore be given to the construction of advanced waste-to-energy facilities which will have to be combined with district heating systems in order to ensure that the heat generated is used in an efficient way. The main problems are firstly, the time required for these changes in the infrastructure and secondly, the high investments involved. For these reasons, the potentials available in the areas of recycling and re-use must be tapped *in parallel with* the improvement of energy recovery systems. The measures taken should be oriented towards the optimisation of the *total* system. It must also be kept in mind that increased efforts in recycling will result in larger and larger amounts of materials in the waste stream, which have already been recycled once or

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[34] The use of PVC in construction (e.g. window frames) is a good example of the volume of waste returned for recycle being much lower than expected.

[35] For example, there is fierce competition among manufacturers of virgin plastics. Domestic manufacturers are currently faced with particularly heavy import competition due to the Asian crisis and moreover, oil prices are very low. As a consequence, e.g. the prices of standard quality PVC and PP (homopolymers) dropped below 1 Deutsch mark at the end of 1998 (1 Deutsch mark = 0.51 EURO = 0.57 US$, data for January–November 1998) [42]. In terms of heating value PP is about half as expensive as gasoline under the German tax system.

[36] Logistics are particularly expensive in high-income countries. This is less true for developing countries where there is also pressure to recycle due to the general scarcity of materials. These are the main reasons why, for example, recycling rates for plastic waste are about four times as high in India compared with Germany ($\sim$90 vs. 22%; value for India include second and third loop recycling, [43,58], additional calculations).

twice. Therefore, it will become necessary to develop appropriate strategies for the second and third cycle. Here, open loop recycling may become more important, e.g. by using plastics waste and rubber waste in road construction [21,44]. In general, the preferred situation is to establish a cascade of mechanical recycling and, finally, to apply feedstock recycling or to extract as much as possible of the energy embodied in the material by incineration. Further research and development on processes and on design for disassembly, recycling and re-use is required [41], in order to increase both the environmental benefits and to reduce the costs and thus reach the ultimate goal of cascading. Apart from the technical improvement measures mentioned, organisational measures and the adaptation of standards will continue to be needed to improve the competitiveness of recycling and re-use [45].

The use of biomass as a feedstock is currently hampered by the low prices of conventional products made from fossil resources. Moreover, the technologies used to manufacture bio-based materials lag behind those of conventional, fossil-based processes, because of the large difference in the amount of experience. As an additional problem, the properties of bio-based material are often inferior to those of competing materials derived from fossil feedstocks (e.g. starch polymers compared with polyolefins). For these reasons, stakeholders suggest concentrating on those biomass-derived products that show specific advantages compared with their conventional counterparts, instead of duplicating compounds which are already being manufactured from fossil resources (personal communication with J. Bozell, National Renewable Energy Laboratory, Golden, USA and D. Wittmeyer, German Association of Chemical Industry).

The potential of energy saving and CO_2 emission reduction by biomass feedstocks will only be small in the short term (see Tables 3 and 4). However, biomass feedstocks could enable large saving potentials in the long term as own calculations for bulk chemicals (see Tables 3 and 4) and analyses by Gielen indicate [46]. This will probably be triggered by new developments in biotechnology, allowing higher yields (e.g. ethanol) and product qualities (e.g. detergents with tailored enzymes) and by new products [47–50]. It is expected that these developments will improve the chances of using bio-based sources as chemical feedstocks [51]. Therefore, it may be worth assessing whether biomass feedstocks are being given sufficient attention in current research and development agendas, including assessments of the potentials and risks.

LCAs should be conducted to compare competing options with producing bio-based materials, and also to compare the most promising of these with the use of biomass for the supply of energy (electricity, heat). Analyses conducted for two case studies show that, depending on the specific application, either the use of biomass for energy or for materials is more favourable; e.g. on the one hand it was shown that the use of biomass for the production of bulk chemicals cannot compete with biomass gasification and electricity generation in terms of fossil CO_2 abatement [29]. On the other hand, there is strong indication that — in terms of the savings in finite energy and GHG emissions — it is more effective to use vegetable oils to produce surfactants as opposed to liquid biofuels [52]. Based on further comparisons, which should also include other environmental indicators, e.g. water-

borne emissions and waste, it will be possible to set quantity targets (not quota) and cost targets for the use of biomass as a feedstock. Non-binding quantity targets already exist for the US where the Department of Energy (DOE) stated that at least 10% of the bulk chemicals should be produced from biomass feedstocks by the year 2020, and that this share should be increased upto 50% by 2050 [53]. In contrast, the goals in Europe have only been set for bioenergy, which is supposed to increase from the current 3% of the total domestic energy consumption to 6% in 2010 (figures for EU-15) [54].

6. Conclusions and policy implications

The manufacture and waste management of synthetic organic materials accounts for a considerable consumption of fossil resources and entails substantial CO_2 emissions. If compared with the entire industrial sector in Germany (without non-energy use[37]) the share is 44% for energy and 20% for CO_2.

It has been shown that the share of synthetic organic materials produced by recycling or re-use is still very low in Germany; the total amount of end products consumed domestically having a share of less than 10%. This already indicates that, in general, recycling and re-use still offer a high untapped potential for energy saving and CO_2 abatement.

In total, the potential savings relative to the various reference cases amount to 220 PJ of finite energy and 14 Mt of fossil CO_2 by the year 2005 (see Table 6). These are substantial saving potentials, even when compared with the current figures for the total German industry, with 6% for energy and 5% for CO_2. Relative to the system analysed in this study (see the dotted box in Fig. 1) an equivalent of 13% of energy and 24% of CO_2 can be saved (uncertainty ranges, 9–17% for energy and 17–31% for CO_2). This leads to the significant conclusion that the saving potential identified on the non-energy side is comparable with that discussed and negotiated for energy efficiency improvement[38]. Compared with the total German economy, the savings identified amount to 1.5% for both energy and CO_2 (see Table 6). Hence, given that some countries may have difficulty in meeting the Kyoto target, the potentials on the non-energy side deserve to be given more attention.

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[37] See footnote c in Table 6 for the energy requirements and CO_2 emissions of the entire industrial sector in Germany.

[38] For example, German trade and industry undertook the commitment to reduce their specific energy-related CO_2 emissions by 20% in the period 1990–2005 [55]. This voluntary agreement refers to CO_2 mitigation by improving energy efficiency. These savings of energy-related CO_2 emissions (20%) refer to the current CO_2 emissions from the energy system (fuels and electricity to power the processes), whereas the saving potential related to non-energy use (24%, see Table 6) refers to the CO_2 emissions both from the energy system and the materials system. This means that the denominators differ in the two cases. Nevertheless, the comparison is valid because the differences between the two denominators are in the range of 10% only (compare Table 2).

As of 2005 direct landfilling of organic materials will be prohibited in Germany. This is very likely to cause a rise in fossil CO_2 emissions[39] unless the *average* efficiency of MSWI plants (including waste-to-energy facilities) increases in comparison to today's figures or larger amounts of waste are recycled and re-used. It is therefore imperative that only highly efficient MSWI plants are built in the future. Moreover, future policies will have to take into account the saving potentials related to recycling and re-use. Optimised strategies combining re-use, mechanical recycling, feedstock recycling, and energy recovery will have to be developed for the various types of waste. To extend the scope of recycling and re-use it is essential to conduct further research and development on processes and design for disassembly, recycling and re-use, and to support the competitiveness of the recycling industries by introducing further measures.

Own analyses show that it is impossible to make a *general* statement about whether products made of biomass sources are to be preferred in terms of finite energy use and fossil CO_2 emissions as opposed to their petrochemical counterparts. Especially those bio-based products that require complicated processing may be less favourable in terms of energy use and CO_2 emissions than their counterparts derived from fossil resources (see PHA).

On the other hand, it must be kept in mind that technological progress is rapid (e.g. due to the progress made in biotechnology), i.e. new processes with an improved ecological and cost performance are under development. In terms of finite energy and fossil CO_2, oleochemical surfactants, lubricants from vegetable oils and starch polymers, offer advantages compared with their petrochemical counterparts even today.

According to the potentials that have been established, recycling, re-use and energy recovery of synthetic organic materials can contribute much towards saving energy and to reducing CO_2 emissions in the short term. For the long term, the use of biomass feedstocks may contribute as much, or even more than recycling and energy recovery strategies (as the calculations for bulk chemicals indicate). This will probably be triggered off by new developments in biotechnology. Therefore it may be worth looking into whether biomass feedstocks are being given enough attention in current research and development agendas, including assessments of the potentials and the risks involved.

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[39] On the other hand, the increased incineration of municipal solid waste will probably result in a substantial decrease of methane emissions originating from landfilling. For the time period covered in this study, these methane emissions practically exclusively originate from natural organic waste, e.g. food waste, and are therefore outside the scope of this analysis which is focussing on synthetic organic materials.

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